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Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles

Shaik Amjad [a,*], S. Neelakrishnan [a], R. Rudramoorthy [b]

[a] Automobile Engineering Department, PSG College of Technology, Coimbatore 641 004, Tamilnadu, India
[b] Production Engineering Department, PSG College of Technology, Coimbatore 641 004, Tamilnadu, India

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ABSTRACT

Automobile drivetrain hybridization is considered as an important step in reducing greenhouse gases and related automotive emissions. However, current hybrid electric vehicles are a temporary solution on the way to zero emission road vehicles. Recently there has been a lot of interest in the concept of plug-in hybrid electric vehicles, which have great potential to attain higher fuel economy and efficiency, with a longer range in pure electric propulsion mode. PHEVs represent the next generation of hybrid vehicles that bridges the gap between present hybrid electric vehicles and battery operated electric vehicles. In this paper a brief review of design considerations and selection of major components for plug-in hybrid electric vehicles is provided. This paper also focuses on the technological challenges ahead of plug-in hybrid electric vehicles in relation to its major components, which are reviewed in detail. The importance of economics and government support for the successful deployment of this plug-in hybrid technology in the near future to achieve national energy security is also discussed in the paper.

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1. Introduction

In recent years, green house gas emissions and exhaustion of natural resources have become serious global issue. The transportation sector is the most rapidly growing consumer of the

* Corresponding author. Tel.: +91 94435 51032.
E-mail address: Amjad72@gmail.com (S. Amjad).

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world's energy, consuming 49% of the oil resources. It is also estimated that, if the oil discovery and consumption follow current trends, the world oil resources will be depleted by 2038 [1]. These concerns drive the automotive researchers and engineers to concentrate on alternate energy systems. Firstly, reducing automotive emissions to control air pollution and global warming. Secondly, dependency on foreign oil must be reduced for both national energy security and socio-economic considerations.

In general, conventional internal combustion engine powered vehicles are more efficient at relatively higher loads. But, most of the time they are operated at lower engine loads and hence they do not have better overall efficiency [2]. The solution is the use of electric vehicles (EVs), which are more energy efficient and have zero tail pipe emissions. However, these vehicles have not been successful because of higher cost, added weight of batteries, reduced load capacity, limited range and lack of recharging infrastructure. Today's hybrid electric vehicles (HEVs) offer improved fuel economy, low emissions and take the advantage of existing fuel infrastructure, but, still depend entirely on petroleum to charge the battery pack. On the other hand, hydrogen and fuel cell technologies have advanced rapidly, but still face significant improvement for effective cost, infrastructure and technical challenges that could limit market penetration for the next 10–15 years. One clear solution that emerges is the need to develop an electric vehicle to meet the needs of city driving as well as weekend and holiday outing of longer distances.

1.1. Plug-in hybrid electric vehicle

A plug-in hybrid electric vehicle (PHEV) is very similar to the conventional hybrid electric vehicles available in the market today. A conventional hybrid electric vehicle depends on petroleum fuels, generating required electricity on-board, whereas a PHEV has a battery pack that can be fully charged by plugging into a standard electrical outlet. In plug-in hybrids the battery pack is the primary source of power for relatively short distances. For longer distances, once the battery has been depleted to a certain state-of-charge (SOC), the vehicle would switch over to hybrid mode. This also includes using energy re-captured from braking (regenerative braking), turning off the engine when the vehicle stops, and allowing the internal combustion (IC) engine to run at a more constant and efficient speed. Depending on the configuration of the vehicle, people who drive less than all-electric range per day could use no fuel at all. A PHEV offers most of the environmental benefits of electric vehicle operation without giving up the advantages of an IC engine based vehicle, such as the ability to refuel if necessary. Fig. 1 illustrates the energy flow in a typical plug-in hybrid electric vehicle.

The plug-in hybrid electric vehicles are the right move towards reduced global emissions, which offer high performance and fuel efficiency in both electric and hybrid mode. The most clear-cut benefit of plug-in hybrids is their ability to reduce petroleum consumption by providing electric only operation for a substantial fraction of daily driving. For instance, if a PHEV operates solely on electricity until reaching its all-electric range (AER) and is charged once per day, then the distance traveled on petroleum on a given day would be the excess of kilometers traveled over the range. One of the attractive features of plug-in hybrid vehicle is that, it permits the use of grid electricity generated using energy sources other than petroleum. Another benefit of PHEV for its owner is that it can be used to power the house or any other standard electric device when there is no power available or the grid power is cut-off [3].

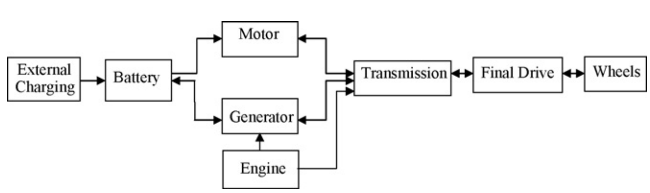

Fig. 1. Plug-in hybrid electric vehicle energy flow diagram.

From a public health perspective, pollutants from power plants are less threatening than emissions from a vehicle, as the latter are released in much closer proximity to individuals. Operating in electric only mode, plug-ins have no tailpipe emissions, providing a potential health benefit. Indirect emissions of plug-ins are the functions of the fuel mix, efficiency of generation, transmission and distribution of the power systems while running on electricity. These emissions represent a much smaller percentage of full fuel-cycle emissions of the pollutants listed for a vehicle operating on electricity than upstream emissions from a vehicle operating on petroleum fuels. Several studies have found that when charged from the grid, plug-in hybrid electric vehicles emit less CO_2 and other pollutants over their entire fuel cycle than conventional vehicles and hybrid electric vehicles. Thus PHEVs may reduce the emissions impact of the transportation sector in many regions where grid electricity is effectively a cleaner source of transportation fuel than petroleum fuels [4]. As a comparison to non-plug-in hybrids, a plug-in hybrid offers 25–55% reduction in NO_x, 35–65% reduction in greenhouse gases and 40–80% reduction in gasoline consumption [5]. With regard to greenhouse gas emissions, plug-ins are more advantageous than hybrids with clean power. Indeed, one of the great advantages of plug-ins is that the electricity used to power the vehicle may come from any combination of energy sources, including coal, nuclear, natural gas, oil or renewable sources such as hydropower, solar or wind. Plug-ins greenhouse gas benefits would grow only in a future scenario in which power sector CO_2 emissions are reduced from present levels.

2. Design considerations and selection of components for PHEVs

In general, design considerations with respect to commercial potential are represented in terms of their prospective operating cost and the economic characteristics with a focus on their market potential. One of the most important issues in design of PHEV is that the vehicle should demonstrate performance (acceleration, maximum cruising speed, etc.) with better fuel economy and less environmental impact. The parameters of PHEV powertrain such as the power capacity of the engine, electric motor and capacity of battery and the transmission gear ratio have a large influence on the vehicle performance, operation efficiency, fuel economy and battery state-of-charge. Therefore, in the design of PHEV, the parameters of the powertrain need to be determined through the optimization process. Once the selection of components like engine, electric motor and battery are completed, the next step is to find a hybrid control strategy that determines how power in a powertrain should be distributed as a function of the vehicle parameters such as drivetrain characteristics, battery SOC and driver's demand. Various design considerations and selection of major components involved in the development of plug-in hybrid electric vehicle are discussed below.

2.1. Electric propulsion motors

The choice of electric propulsion system for PHEVs is mainly dependent on a number of factors, including driver expectation, vehicle constraints and energy source. Driver expectation is defined by a driving profile, which includes the acceleration, maximum speed, climbing capacity, braking and range. Vehicle constraints include vehicle type, vehicle weight and payload. The

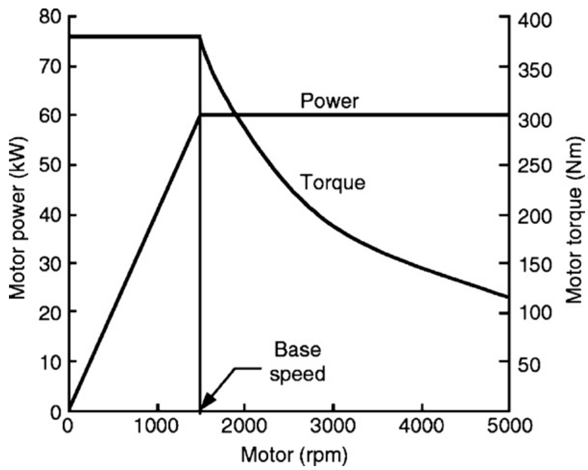

Fig. 2. Performance characteristics of a typical electrical motor for traction [1].

efficiency in motor is derived by multiplying the charging and discharging efficiency of the battery [6].

Generally, the internal combustion engine significantly loses efficiency in a low-load range, while an electric motor shows higher efficiency in all areas. Fig. 2 shows the typical performance characteristics of electrical motors for traction, usually have speed–torque characteristics that is much closer to the ideal [1]. Several types of electric motors can be considered for plug-in hybrids. Direct current (DC) series motors are easy to operate and control. However, they have a low power to weight ratio (typically 1HP per 7.3 kg). DC motors need commutator and brushes to feed current into armature, thus making them heavier, less reliable and undesirable for maintenance-free operation and speed. Its lower cost and the elimination of a sophisticated inverter offset the increased weight of the motor. In comparison, DC brushless motors exhibit high power to weight ratios and are very efficient (about 95%) [7]. Alternate current (AC) induction motors are widely accepted as commutatorless motors, because of their low cost, high reliability and maintenance-free operation. The induction motors have certain inherent disadvantages such as speed which is not easily controlled, low lagging power factors when lightly loaded with starting current, usually three to seven times full-loaded current [8]. Switched reluctance motors (SRMs) have high speed operation capability with a wide constant power region. These motors have high starting torque and high torque–inertia ratio [9].

The dramatic improvements in permanent magnet materials and power electronic devices over the last two decades have led to the development of brushless permanent magnet (PM) motors that offer significant improvements in power density, efficiency, noise/vibration reduction and no electrical sparks. Permanent magnet synchronous motors (PMSMs) are more efficient and easier to cool, due to the absence of rotor copper loss. PMSM seems to be the best option for plug-in hybrids [10]. A permanent magnet synchronous motor, which uses PM material such as NdFeB to generate a magnetic field has the higher efficiency (95%) compared with induction motor or DC motor. The major shortcoming of PM motors is the cost due to the high energy magnets [11].

At present, of the various types of motors available for PHEVs, switched reluctance motors and permanent magnet motors are the preferred choice.

2.2. Energy storage devices

Right now the biggest concern for plug-in hybrids is the selection of type of battery. Typically, PHEVs provide greater amounts of on-board energy storage than HEVs by incorporating larger batteries. This larger battery size creates the possibility for displacing substantive amounts of fuel for the engine with electricity from the electrical power grid. For, plug-in hybrid electric vehicle designs intended to have significant all-electric range, the energy storage unit must store sufficient energy to satisfy the driving range requirements. The electrical energy storage units must be sized so that they store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles. In addition, the energy storage unit must meet appropriate cycle and calendar life requirements. The batteries in this application are regularly deep discharged and recharged using grid electricity. Hence, cycle life for deep discharges is a key consideration and it is essential that the battery meets a specified minimum requirement. With all battery chemistries, there are tradeoffs between the energy density and useable power density of the battery [12].

Lead acid batteries have low energy density typically around 30 Wh/kg whereas nickel-metal hydride (Ni-MH) batteries have an energy density of about 70 Wh/kg. Although Ni-MH batteries have considerable energy density than lead acid batteries, they have lower charging efficiency. Whereas, lithium-ion (Li-ion) batteries have energy density as high as 180 Wh/kg [4]. Lithium-ion and lithium polymer batteries represent some of the most promising developments in the area of electric and hybrid vehicles. Fig. 3 shows the volumetric energy density (Wh/L) with respect to gravimetric energy density (Wh/kg) for different variety of batteries. New lithium-ion batteries seen from lab tests are able to last 10 years or more. Hence, lithium-ion batteries pack more energy density and specific power into a smaller battery package. The volume and weight savings (about 60%) over a Ni-MH battery means less weight and more space for comfort in the vehicle [13].

A PHEV is likely to incur at least one deep discharge cycle per day resulting to 4000 plus deep discharge cycles in its 10–15 years lifetime. Fig. 4 shows the expected life cycle performance of lithium-ion and nickel-metal hydride technology as a function of the discharge depth. It shows that when a battery is discharged more deeply, the cycle life decreases. The horizontal, shaded box is showing the depth of discharge cycling that HEV batteries today incur. The vertical, shaded box is the range of cycles that a PHEV battery will need to endure for a 10–15-year vehicle life. The literature indicates that Ni-MH can achieve 4000 cycles when discharged to 70% depth of discharge repeatedly. To achieve the same number of cycles, Li-ion technology could only be discharged to 50% depth of discharge on a daily basis [14].

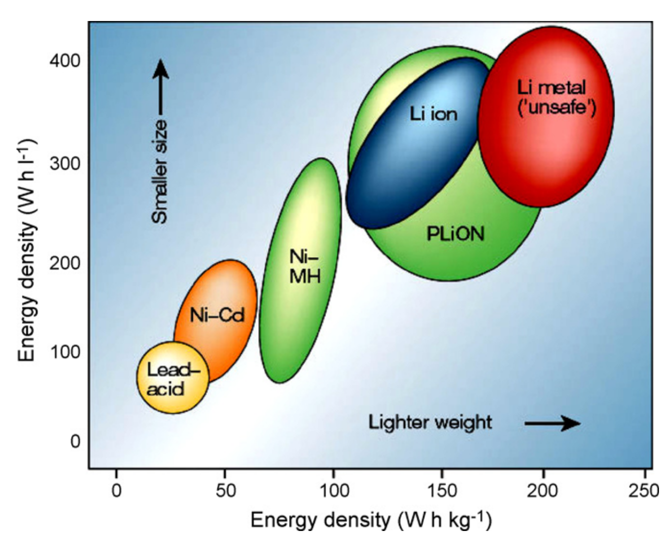

Fig. 3. Comparison of different battery technologies in terms of volumetric and gravimetric energy density [13].

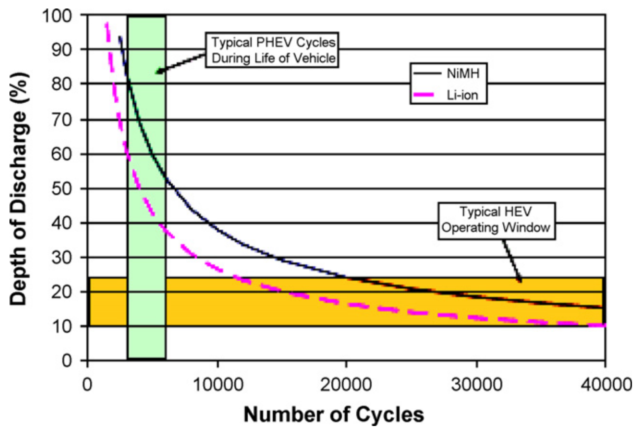

Fig. 4. Cycle life characteristics of energy storage technologies [14].

From the various battery types available at present the nickel-metal hydride and lithium-ion batteries represent the preferred choice for plug-in hybrid electric vehicles.

2.3. Control strategy

The effectiveness of fuel consumption depends not only on vehicle design but also on the control strategy used. The control strategy provides a dynamic control of the vehicle to ensure the best utilization of the onboard energy resources for the given operating conditions. This can be accomplished by controlling the output level of the auxiliary power unit to ensure the highest possible combined efficiency of energy generation and energy exchange with the storage device. So, the energy management strategy is extremely important to decide how and when energy will be provided by various sources of PHEV.

Generally, conventional HEVs are charge-sustaining i.e., while driving they maintain their batteries at a roughly constant state-of-charge (SOC) and recharging occurs only from on-board electricity generation by internal combustion engine fuelled by petroleum fuel and the recapture of kinetic energy through regenerative braking. In contrast, PHEVs can operate in either charge-sustaining or charge-depleting mode. As the name suggests, in charge-depleting mode the vehicle depletes the battery's SOC. While PHEV designs can vary considerably, one design is to operate first in charge-depleting mode, then switch to charge-sustaining mode once the battery SOC reaches a design minimum. In a PHEV, the strategy will attempt to bias the energy flow from battery pack when it exhibits a high SOC. As the SOC of the battery pack begins to fall, the strategy will bias the energy usage more from the IC engine in order to maintain SOC and to prevent damage to the battery pack and reduced cycle life.

PHEV designs provide all electric operation for some limited distance, known as the all-electric range (AER). Since short trips represent the majority of driving in cities, the result would be a dramatic decrease in fuel consumption and urban pollution. A PHEV20, for example, is a PHEV with 20 miles (32 km) of AER. This distance is determined by size of the battery, the SOC threshold between charge-depleting and charge-sustaining modes, the size of the electric motor, power electronics, and energy and power demands resulting from driving conditions, e.g., acceleration, distance, payload, etc. Electrification of miles through charge-depleting operation in a PHEV is expected to be a cost-effective way to continue to reduce fuel consumption beyond HEV technology capabilities [15].

The designed control strategy does not necessarily provide maximum fuel savings over all driving demand. A United States personal transportation study estimates that 50% of Americans drive 25 miles (40 km) or less per day, and 80% drive less than 50 miles (80 km). A useful analysis of over 10,000 cars journeys throughout Europe found that the total daily distances traveled were mostly less than 55 km [4].

Therefore, choosing the right electric range to handle the daily driving needs is essential and car producers are expected to produce PHEVs with different all-electric ranges for their customers. The control system should utilize a strategy modified in real time depending on the input from various sensors at different locations in the system. An approach that employs route based control could improve PHEVs efficiency with software changes.

3. Technological challenges ahead of PHEVs

Several technologies to be implemented in the next generations of automobiles are found on the horizon. There are still a lot of technology challenges to overcome, particularly in the area of plug-in hybrid electric vehicles. Hence, the present challenges for researchers are in the development of low weight and high capacity batteries, drives, electronic controls and transmission. Some of these technological challenges are discussed below.

3.1. Energy storage devices

Most hybrid hardware subsystems and components with exception of energy storage devices have been matured to an acceptable level efficiency performance and reliability. As per the studies, the energy stored in the HEV storage unit is much smaller i.e., in the range of 26.3–77 Wh/kg than that in the EV unit which is in the range of 34.5–140 Wh/kg. It is also clear that the power capability of the batteries designed for HEVs is much higher i.e., in the range of 77–745 W/kg than those designed for EVs which is in the range of 40–255 W/kg. However, batteries for plug-in hybrid electric vehicles require both high energy density and high-power capability based on the driving requirements. Battery characteristics for EV and HEV applications are given in Table 1. It is seen from Table 1 that batteries for HEVs are quite different compared with those for EVs in several ways [12]. And much less work has been done to develop batteries for plug-in hybrids, but it is likely their characteristics will be intermediate between those of EVs and HEVs. In addition, recycling of used batteries and the recycling cost on a per-vehicle basis also need to be addressed in future. Other alternative energy storage units including ultracapacitors and flywheels need to be investigated.

The batteries efficiency is affected by several factors including temperature, driving patterns i.e., city driving/highway driving, charging patterns, etc. Maintaining optimum, uniform tempera-

Table 1
Characteristic of various technologies/types of batteries for use in vehicle applications [12].

Battery technology	Application type	Ah	Wh/kg at C/3	W/kg 95% eff.
Lead acid				
Panasonic	HEV	25	26.3	77
Panasonic	EV	60	34.5	47
Ni-MH				
Panasonic	HEV	6.5	46	207
Panasonic	EV	65	68	46
Ovonic	HEV	12	45	195
Ovonic	EV	85	68	40
Li-ion				
Saft	HEV	12	77	256
Saft	EV	41	140	90
Shin-Kobe	HEV	4	56	745
Shin-Kobe	EV	90	105	255

HEV: hybrid electric vehicle; EV: electric vehicle.

ture or some method of thermal management is essential to obtain peak battery performance. Under cold temperature conditions, the capacity of the battery may be only at 70% of its rated capacity [16].

For plug-in hybrids, battery cycle life becomes an important issue. The battery will be recharged from a low state-of-charge (after deep discharges) more often than for the battery powered EV. As a result, the battery cycle life requirement for plug-in hybrids will be more demanding than for pure EV. A minimum of 2000–3000 cycles will be required. Hence, both in terms of power and cycle life, the plug-in hybrid application is more demanding for the battery than the EV application [12]. PHEV users would expect the battery to last the life of the vehicle. The frequent recharging and overcharging loses its ability to take and hold a new charge. In plug-in hybrids, batteries will be charged up to at least 95% and then deeply discharged during the AER of driving before settling into a hybrid mode. Such deep discharging typically decreases battery life. Battery life can be extended by increasing the size for a given application, a larger battery will require a lesser percent discharge than will a smaller battery and consequently will have a longer life. However, the use of larger batteries would of course increase cost, size and weight.

The nickel-metal hydride battery durability, specific power and high temperature operation have improved substantially, suggesting that a battery pack lasting the life of the vehicle may be within reach. Li-ion batteries are a much newer design still seeing major advances. They offer power and energy densities higher than those of Ni-MH, which lead to physical advantages for a given amount of energy storage Li-ion batteries that can take up one-quarter the size of Ni-MH batteries and weigh approximately half as much. But the durability, cost, and safety of Li-ion batteries still need improvement [5]. But there is a need for significant research to be done before lithium-ion batteries are ready for commercialization to achieve improved performance, life, tolerance to abusive conditions (such as overcharge) and reduced cost.

Any battery is potentially unsafe when mishandled or subjected to trauma such as physical blows, extremely high temperatures, or fire. Even though a vehicle is safe under normal conditions, a great deal of testing is required to determine its safety in a crash or fire. New battery technologies will require extensive testing before they are deemed suitable for in-vehicle use. Emergency responders must also learn how to handle new vehicle battery technologies safely in the event of a crash or fire.

The first and primary challenge is the validation of battery characteristics capable of meeting PHEV operation requirements. This is a considerable challenge which has been under evaluation for the couple of years, but this work has made tremendous progress. The development of a robust supplier base is an important second challenge. So, it is important to increase the potential pool of component users and component suppliers so that economies of scale can be generated as quickly as possible. The third challenge is the coordination of a safe and usable set of charging standards. Owners need to know that charging their vehicles is as safe and easy as charging their cell phones. This is the easiest challenge to meet from a technical standpoint, but it will require active participation from regulators, automotive industry, and electric power industry.

The other significant technical challenges include higher initial cost, cost of battery replacement, added weight and volume, performance and durability. Future challenges will include verifying lifetime testing in field testing, and developing production facilities to ramp up the availability of this technology.

3.2. Electric propulsion motors

In the area of propulsion motor and other motor control technologies, methods to eliminate speed/position sensors, inverter current sensors, etc., have been under investigation for several years. These technologies have not yet been proven to be practical for automotive applications [17–23]. The technology development effort needs to be focused on the sensorless operation of electric machines and the reduction or elimination of current sensors in inverters. Controllers need to be developed for the robust operation of all vehicle subsystems. The development of low cost, high temperature magnets would lead to the widespread use of permanent magnet (PM) motors. PM motors have higher efficiency and need lower current to obtain the same torque as other machines. This would reduce the cost of power devices as well. This cost reduction is critical for market viability. The future technological challenges for the electric motors will be light weight, wide speed range, high efficiency, maximum torque and long life.

3.3. Power electronics

The power switching devices and associated control systems and components play a key role in bringing plug-in hybrid vehicles to market with reliability and affordability. The power electronic system should be efficient to improve the range of the electric operation and fuel economy. The selection of power semiconductor devices, converters/inverters, control and switching strategies, the packaging of the individual units, and the system integration are very crucial to the development of efficient and high-performance PHEVs. In addition to power devices and controllers, there are several other components such as capacitors, inductors, bus bars, thermal systems that form a major portion of a power electronic unit. The packaging of all these units as one system has significant challenges. To meet the requirements of the automotive environment, several technical challenges need to be overcome, and new developments are necessary, from the device level to the system level [24].

The technologies related to device packaging need to be investigated by the semiconductor industry to develop a power switch. Wire bonding, device interconnections, etc., are the barriers to the development of high-current-density power units. Technologies such as topside power connection without wire bonds, minimizing wire bonds, dynamic matching, heat-sinking both sides of the die, direct bond copper on alumina and aluminum-nitride substrates, interconnect solutions for large-scale manufacturing, etc., need to be investigated as well. The reliable operation of power modules and other related packaging technologies needs to be studied. The power electronic systems available in the market are still bulky and difficult to package for automotive applications. The capacitors with high-frequency and high-voltage operations, low equivalent series resistance, high operating temperatures, and high ripple current capabilities need to be further developed. Hence, improved dielectric materials need to be investigated. The technology of laminated bus bars with high isolation voltage and low inductance needs further work to meet the automotive operating environment.

In order to meet the packaging goals, the components must be designed to operate over a much higher temperature range. A novel way of cooling the entire unit needs to be examined to quickly take away the heat from the devices. The current heat management techniques are inadequate to dissipate heat in high-power density systems. In addition, the impact of current intensiveness in a system on lower efficiency, larger passive components such as inductors and capacitors, and a thicker wiring harness among the components should be properly taken into consideration at the stage of system design. Also there is a need to develop an inverter topology that achieves the performance of a soft-switched inverter but with less components and simplified control. Topologies with two or more integrated functions such as

an inverter, a charger, and a dc/dc converter and with minimum use of capacitors need to be developed. In the area of dc–dc converters, further development is needed to obtain 12 V from 42 V and higher voltages.

3.4. Other technological challenges

Minimizing the energy consumption at the vehicle systems' level must be accomplished by reducing weight, aerodynamic drag, rolling resistance and emission characteristics through the use of light materials, aerodynamic vehicle designs, advanced technologies that can reduce the friction and improved system efficiency. Hence these technologies provide energy management advantages while helping keep the cost of fuel efficiency affordable to the customer.

3.4.1. Light weight materials

An effective way to improve energy efficiency is to reduce the overall weight of the vehicle. Therefore, the use of advanced materials with high strength to weight ratio, such as composite or plastic body panels, light weight aluminum structural components can also improve safety while reducing weight, if more sophisticated structural designs are used. The development of injection-moulded thermoplastic vehicle body technology reduces weight while reducing the cost below that of a conventional steel body and far below other light weight materials such as aluminum, titanium or thermo-set composites. The body system is calculated to weigh 46% less and 15% less costly to manufacture than comparable steel body [25].

3.4.2. Aerodynamics and low resistance tyres

Manufacturers are now focusing on aerodynamic drag and tyre rolling resistance for improved aerodynamics and hence reduce fuel consumption, habitat noise and also provide the driver with more control and stability. Wind resistance can be decreased through redesigning the body to a more aerodynamic shape. In addition, the use of slippery body panels can further decrease the aerodynamic drag. Another way to improve efficiency is to decrease rolling resistance caused due to the friction between wheels and road. Rolling resistance can be limited through the use of low resistance advanced design tyres [26].

4. Economics

Plug-in hybrid vehicle is not considered economical taking into account the extra battery cost. Choosing the right electric range to handle the daily driving needs is essential and automobile manufacturers are expected to produce PHEVs with different all-electric ranges for their customers. Good analysis and research will enable buyers to choose vehicles that best meet their needs while enabling them to consume less fuel, all the while minimizing the payback period for the increased purchase price. There is no question that the widening gap between electricity prices and petroleum prices will make PHEVs more attractive in the long term. The viability of plug-ins will depend upon cost as well as performance. Although a plug-in hybrid vehicle will initially have a higher price than a conventional vehicle, the differential is bound to diminish with time. Electricity cost is much lower compared to petroleum fuel and also plug-in hybrids can be charged from the grid late at night. The use of PHEVs would increase electrical demand that could actually be beneficial, because the increased demand would typically occur at night, during off-peak hours. This would allow the utilities to better balance their electricity production loads, leading to improved operating efficiencies [27].

Battery cost is a major hurdle to the commercialization of plug-ins with extensive electric only range. Battery costs are dependent upon a range of parameters, including type, materials, design and production volume. Battery designs with lower power-to-total-energy ratios (kW/kWh) are a configuration more appropriate for plug-in hybrid use. Lithium-ion batteries are currently more expensive than Ni-MH batteries. Also as battery technology improves, the plug-in hybrids will be more successful. As production volumes increase, cost will come down with the induction of automated manufacturing lines and economies of scale. Fig. 5 shows the trend of reduction in battery cost with increase in production volume [28].

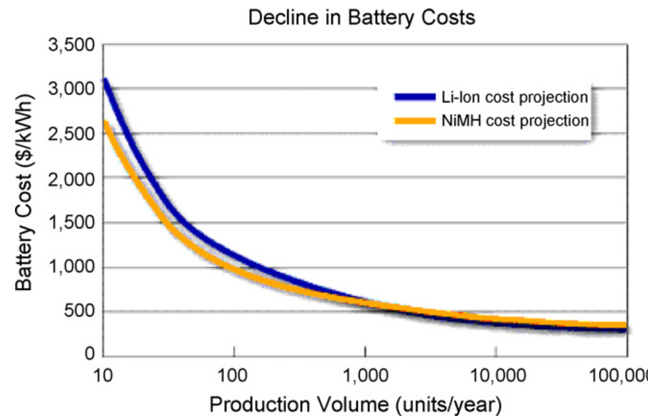

Fig. 5. Battery production volume vs battery cost [28].

The motor and batteries in these vehicles require very low maintenance over the life of the vehicle. The engine also does not need any more maintenance than in any other IC engine powered vehicle. Because these plug-in hybrids have regenerating braking, brake pairs may even last longer than those in normal cars. However, as the battery life increases in the future, the costs will come down and the economics gets better. Old batteries must be recycled to reduce cost on a per-vehicle basis once all transport, processing, and disposal costs are considered. Also, power electronics need to be made smaller, simpler and less expensive.

5. Government support and incentives for the deployment of PHEVs

The choice of electricity to power the PHEVs of tomorrow is critical and large number of factors must be weighed. This choice needs to consider not only the advanced technology but also the safety and health considerations, overall infrastructure costs, fuel cost on a tax neutral basis and acceptance by the public. The main question is whether there is enough interest on the part of the government and vehicle customers to encourage the industry to commercialize this technology. The following measures can be taken as important steps by the government to accelerate the development and deployment of plug-in hybrid electric vehicles:

- Establish a program with the automotive manufacturers to create prototype demonstrations with a focus on near-term applications.
- Develop a plan for acquiring a fleet of plug-in hybrid electric vehicles in various configurations to be operated in multiple locations across the country.
- As fleet data becomes available, the government can collect and share the operating data appropriately and inform the consumers and fleet operators about the benefits of plug-in hybrid technology.
- Direct the appropriate regulators to develop a certification test protocol for plug-in hybrid drive systems to maximize the benefits received by the manufacturer and consumer.

- Create an awareness program to the general public on the attributes of plug-in technology. In addition, create a program which reaches the university level to educate science and engineering students on all types of electric-drive technology.
- Direct the national research programs to focus on increasing the performance of batteries, electric-drive systems, power electronics and related system developments.

Some of the incentives that could help are:

- A tax rebate on the upfront costs of the vehicle due to the cost of the batteries for a few years.
- The auto companies should agree to standardize on some battery parameters that would allow the battery technology to grow, but allow the auto industry to build the vehicles.
- The government should encourage this type of transportation because it greatly improves the society's transportation efficiency.

6. Conclusions

Plug-in hybrid electric vehicles (PHEVs) represent the next generation of hybrid vehicles that offer important advantages over the cleanest and most efficient of today's hybrid vehicles. However, there are several design and technological basic challenges to be overcome.

The design considerations include reduction in weight, volume and cost to achieve the expected efficiency and performance. By adopting better design considerations in vehicle design with optimized control strategy developed for different kinds of driving patterns and selection of suitable components, it is possible to achieve better energy efficiency with these vehicles.

Also, technological challenges related to energy storage system, motor drives and associated power electronics need to be addressed. These challenges can be summarized as follows:

- There is a need to develop batteries for PHEVs, whose requirement characteristics like energy density and specific power will be intermediate between those of EVs and HEVs. There is also a need to improve the battery life, number of deep discharge cycles and charging/discharging efficiencies even under cold climatic conditions. A great deal of testing is required to determine its safety in a crash or fire.
- For electric propulsion motors, the future challenges will be light weight, wide speed range, high efficiency, maximum torque and long life. Controllers for these motors also need to be developed for the robust vehicle operations.
- Reliability and affordability of power switching devices and associated control system need to be studied. Also technologies related to device packing and large-scale manufacturing need to be investigated.

PHEVs should also take advantage of research and development in aerodynamics and advanced light weight materials to reduce vehicle weight and hence conserve energy. These vehicles will help the government in its role of promoting energy security and environmental protection, when successfully marketed to consumers. Efforts are also to be taken for provision of affordable and accessible infrastructure for recharging and replacing batteries.

Hence, thrust in research and development on the aforementioned design considerations and technological challenges coupled with government support in terms of incentives to the automobile owners and to the manufacturers will go a long way in hastening the deployment of PHEVs.

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